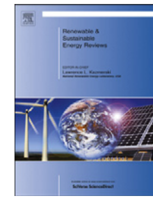
Renewable and Sustainable Energy Reviews 22 (2013) 187–197

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Renewable energy and nuclear power towards sustainable development: Characteristics and prospects

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ARTICLE INFO

Article history:
Received 22 May 2012
Received in revised form
23 January 2013
Accepted 26 January 2013
Available online 1 March 2013

Keywords:
Renewable energy sources
Nuclear energy
Sustainable development
Comparison

ABSTRACT

Today there are several opportunities for Renewable Energy Sources (RES), as well as for nuclear technologies to contribute to mitigating climate change and to promote sustainable development (SD). In this framework, the main scope of the present study is to provide an analysis and a direct point-to-point comparison of five promising renewable energy technologies, namely, biomass gasification, molten carbonate fuel cells fed with wood gas, Solar Photovoltaics (PV), solar thermal and offshore wind, in contrast to two advanced nuclear technologies, European Pressurized Reactor (EPR) and European Fast Reactor (EFR). The examination was made with regards to technology characteristics, sustainability factors and potential deployment drivers and barriers, obtained from relative studies. The analysis indicated that the examined RES and nuclear technologies both offer substantial contribution to climate change by effectively producing limited amounts of GHG emissions, which are close to zero for the nuclear technologies. The RES produce no significant waste and are generally favored by policy incentives, but some of them are plagued by high production costs and low efficiency. On the contrary, the examined nuclear technologies, despite their enhanced safety, reduced costs and minimized waste, still have to face the major issues of weapons proliferation, safety, waste handling and high costs as well as public acceptance, which have been affected by the recent Fukushima accident.

Contents

1. Introduction

Global warming is currently considered as one of the most critical problems that the environment may be faced within the

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.01.035

next 50 years [1]. One of the most important factors of today's global energy production system are Greenhouse Gas (GHG) emissions from power plants around the world, which are considered to be one of the main factors leading to climate change [2]. GHG emissions include carbon dioxide (CO_2), methane, nitrous oxides, chlorofluorocarbons and water vapor which, upon release, contribute to heating up the lower layers of the atmosphere. Attempts to tackle global warming require the increase of use of energy sources alternative to traditional fossil fuels, such as lignite, coal and gas, which release large amounts of GHG [3]. Both nuclear and renewable energy are believed to be able to provide partly solutions to climate change.

Electricity generation from RES is today a promising option, which contributes to the reduction of high dependence on imported energy and provides additional environmental benefits with regards to GHG emissions, thus playing an important role in mitigating climate change [4,5]. The deployment of RES has been large during the last decade [6]. National policy incentives, such as the feed-in-tariff, and mechanisms of the Kyoto protocol, such as the Clean Development Mechanism (CDM), have aided to this deployment. Actually, the ratification of the Kyoto protocol has made the use of RES more advantageous in the race to cut back on GHG emissions [7]. Many countries have included RES investments in their strategy towards reducing dependence on oil and gas imports and the respective price volatilities, as well as mitigating GHG emissions [8]. RES can also be suitable for less developed countries as relatively low capital demanding and decentralized options. However, a large-scale basis deployment of RES faces important economic and technical feasibility limits, even if effective potential reserves are well documented [9].

Nuclear energy plays an important role today in meeting the energy needs of many countries and at the same time in mitigating GHG emissions. Adamantiades and Kessides [10] argue that nuclear plants worldwide contribute significantly to mitigating GHG emissions, whereas they save about 10% of CO_2 emissions from world energy use. Nuclear power plants have played a major role in reducing the amount of GHG produced by the electricity sector in OECD countries [11]. Furthermore, it is claimed that without nuclear power, the EU power plant carbon dioxide emissions would have been about one-third higher [12]. In contrast to North America and most countries of Europe, where nuclear power capacity has remained almost steady for the last two decades, the nuclear capacity in Asia has been growing significantly, as a number of countries in East and South Asia, most notably China, India and South Korea, are planning and building new reactors [10].

Nuclear power and renewable energy are perhaps two of the most powerful tools to bring down the carbon intensity of commercial energy supply today. The majority of the world's electricity in 2010 was produced via fossil fuels, as seen in Fig. 1, while RES accounted for 18% and nuclear power for 14% [13]. Taking into consideration the growing energy demand under the volatile energy prices for traditional fossil fuels (coal, gas, and oil), the need for alternative energy sources exists. This is strengthened by the fact that fossil fuels is not an infinite source of energy, since various studies have indicated for example that the time peak of crude oil production is very near or has passed, although the exact timeframe is under discussion [14–18]. As the global energy needs are constantly increasing, countries have the option to invest in nuclear and/or renewable technologies, in order to satisfy growing energy demands and at the same time contribute to climate change mitigation.

A number of studies in the international literature focus on the integration of renewable energies and nuclear power in the energy market [19,20]. Adamantiades and Kessides [10] explored the current status and future prospects of nuclear energy for sustainable development. Apergis et al. [21] used causality and data from 19 countries to show that the use of nuclear energy has contributed to the reduction of CO_2 emissions, while renewable energy has not yet reached a significant level of contribution. Menyah and Wolde-Rufael [8] agree on the previous statement, having used Granger causality on data regarding the United States. In addition, Forsberg [4] and Verbruggen [22] explored the common future of electricity production from a possible coupling of renewable sources and nuclear power by providing real and full priority to the sustainable options. However, to the best of our knowledge, there is no paper presenting a transparent point-to-point comparison and approach of promising RES and nuclear technologies taking into consideration their potential and perspectives for deployment and enhancement of global sustainability. In this context, the main scope of this study is to analyze and compare specific promising RES options and new nuclear technologies, in terms of their potential of contributing to climate change mitigation and sustainable development, as well as to discuss their differences and possible future trends. For this purpose, two new nuclear technologies, the European Pressurized Reactor (EPR) and the European Fast Reactor (EFR), and five promising renewable technologies, biomass gasification, molten carbonate fuel cells fed with wood gas, offshore wind farms, solar photovoltaics and solar thermal power plants have been chosen.

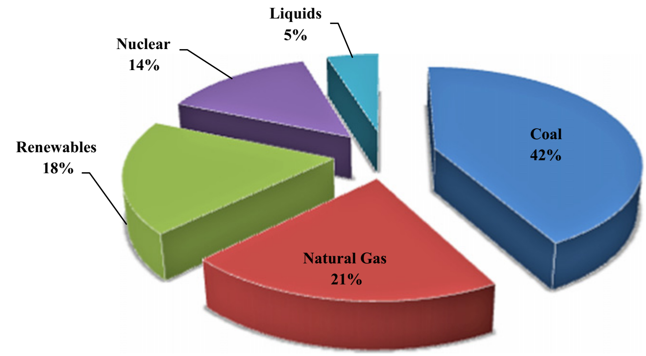

Fig. 1. World net electricity generation by energy source.
Source: Ref. [3].

Apart from the Introduction, the paper is structured along four sections. The approach followed is presented in Section 2. Sections 3 and 4 focus on the analysis of the five renewable energy technologies and the two nuclear energy technologies, respectively. Further on, Section 5 discusses the differences and potential of these technologies to contribute to GHG emission reduction and SD. Finally, Section 6 presents the conclusions that summarize the main points arisen from this study.

2. Presentation of comparison approach

The general philosophy of the proposed approach adopted for the coherent presentation of the technology options is shown in Fig. 2. In order to compare the different technologies, certain characteristics of each have been assessed and presented, as mentioned in the bullets below. Data for the presentation has been partly based on research conducted within the framework of the FP-6 project "New Energy Externality for Development and Sustainability (NEEDS)", as well as taken from the literature. Each technology presented is not country-specific, but universal, according to the geology and climate potential.

In particular, the investigation focused on the following aspects:

- *Technology characteristics and cost details*: Basic technical characteristics of each technology, such as fuel type, electric

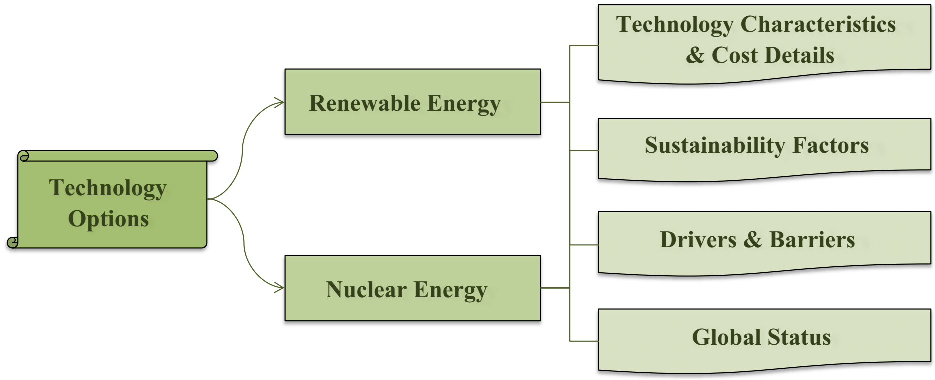

Fig. 2. Technology presentation approach.

efficiency and load factor are presented, including net capital cost and cost of electricity produced. The data used for the RES technologies are typical representatives of each technology and cannot be regarded as fixed. The actual data varies depending on plant studies, location and manufacturer. Regarding nuclear technologies, the data is much closer to the actual, since it regards specific technologies and manufacturers.

- *Global status*: The current global status and future prospects of each technology is examined.
- *Sustainability factors*: The specific sustainability factors considered are assessed in terms of:
  - *Environmental factors*: GHG emission (life-cycle), type of waste produced (life-cycle);
  - *Social factors*: Public acceptance, possible proliferation or misuse, labor mix for technology chain, visual disturbance, noise.

    Numerous sustainability factors exist, that could have been illustrated here, but this exceeds the purposes of the present study. Instead, specific factors were chosen for this study, in order to concisely show the impact of each technology and its sustainability prospects. The GHG emissions focus mainly on CO_2 and include the entire life-cycle of each technology. They were calculated from life-cycle inventories developed and used in the "NEEDS" project.
- *Drivers and barriers*: The technologies are examined as to which extent their implementation is presently hindered or favored by a number of economic, technical and social factors. Examples of such barriers/drivers are: implementation costs and energy costs; lifetime; reliability; safety issues; competitive technologies; energy security and the existing domestic legal/institutional framework.

Most of the above aspects are illustrated in respective tables as well, so as to be easier to compare. A discussion following the presentation of the above parameters clarifies the above parameters and gives a more complete picture of the comparison.

3. Promising RES technologies

Several types of RES technologies, such as wind energy, biomass and solar power have known widespread global growth during the last decades. In 2011 a total of 257 billion USD were invested in new renewable energy capacity [6]. In the power sector specifically, RES accounted for almost half of the estimated 208 GW of electric capacity added globally during 2011. Wind and solar photovoltaics (PV) accounted for almost 40% and 30% of new renewable capacity, respectively, followed by hydropower (nearly 25%). By the end of 2011, total RES power capacity worldwide exceeded 1360 GW, which is 8% over 2010 [6]. The main technical characteristics of each RES technology options examined are described in the following paragraphs.

3.1. Biomass gasification

Based on up-to-date combustion technologies, Combined Heat and Power (CHP) plants can use biomass for power generation, along with heat [3]. Biomass CHP plants are considered mature technologies and short rotation coppiced poplar and straw can be used as fuel for the gasification process [23]. Table 1 summarizes its basic energy and cost characteristics in comparison to the other RES technologies examined. The gas turbine of the biomass CHP plant is considered to have a typical capacity of 9 MWe, while its overall efficiency of conversion to electricity is about 30% [24]. It has notably the highest load factor of all RES examined, since it is continuously fed with gas from the biomass gasification process and the second highest capital cost after Solar Thermal Power Plants. The average electricity cost calculation ranges from 6.51 to 7.29 €cents/kWhe [24]. The life-cycle GHG emissions from these biomass systems (see Table 2) are estimated to be 260 g CO_2eq/kWhe for poplar and 150 g CO_2eq/kWhe for straw, higher than all of the other RES technologies [24]. Apart from the use of poplar/straw, mono-combustion was considered in the gasification process as well as a steam turbine for the production of electricity and heat. For the calculation of the life-cycle inventory, instead of a potential allocation, an alternative use of the residue (poplar/straw) is considered. In the case of poplar, no other use is assumed. Since a sustainable forestry is supposed, taking out the wood diminishes the feedback of nutrients into the soil not significantly. Therefore, no extra expenditure is accounted for. In the case of straw, plowing it into the soil is regarded as a typical alternative use. For this reason, the loss of nutrients fed back into the soil is considered [24].

The technology chain, which includes forestry, harvest, transport, plant construction and operation, produces low chemical waste. The public acceptance for this technology is considered moderate, also due to the visual disturbance caused by the periodic clear cutting for wood and truck traffic for transport, and the noise it emits during operation depends mostly on the traffic transporting the poplar/straw. These sustainability factors are depicted in Table 2. This specific technology faces specific barriers for deployment, which are related to the lack of effective

Table 1
RES technologies characteristics and costs.

Characteristics	**Units**	**RES technologies**							
		Biomass CHP poplar	Biomass CHP straw	Fuel cells MCFC	Offshore wind farms	Solar PV-Si plant	Solar PV-Si building	Solar PV-CdTe building	Solar thermal power plants
Fuel type		srf poplar	Waste straw	Wood gas	Wind	Sun	Sun	Sun	Sun
Electric efficiency	%	0.3	0.3	0.5	0	0	0	0	0.185
Electric generation capacity	MW	9	9	0.25	24	46.63	0.42	0.84	400
Load factor (expected)	hours/year	8000	8000	5000	4000	984	984	984	4518
Annual generation (expected)	GWh/year	72.0	72.0	1.25	96.0	45.9	0.413	0.826	1810
Construction time	Years	2	2	0.83	2	2	0.5	0.5	3
Plant life	Years	15	15	5	30	40	40	35	40
Capital cost (net present value)	€/kWe	2280	2280	1544	1130	848	927	927	3044
Total capital cost (net present value)	M€	21	21	0.4	27	40	0.4	1	1217
Average electricity cost	€cents/kWhe	7.29	6.51	8.44	7.27	6.30	6.92	7.15	6.31

Table 2
Sustainability factors of RES technologies.

RES technologies	**Sustainability factors**						
	GHG emission estimate (life-cycle)	Type of waste	Record of past public acceptance	Possible proliferation or misuse	Labor mix for technology chain	Visual disturbance	Noise
Biomass CHP poplar/straw	Poplar: 260 g CO_2-eq/kWhe, Straw: 150 g CO_2-eq/kWhe	Low chemical waste for full technology chain	✓ Moderate for gasification and generation plant ✓ Requires acceptance of biomass harvest and transport	None	Forestry, harvest, transport, plant construction and operation	Periodic clear cutting for wood, truck traffic for transport	✓ Local plant noise ✓ Traffic noise, if through populated areas
Fuel cells MCFC wood gas	50 g CO_2-eq/kWhe	Moderate chemical wastes for full technology chain, with relatively less for wood gas	✓ Distributed nature means public acceptance is not a critical issue ✓ Wood gas requires acceptance of wood harvest and transport	None	✓ Manufacturing installation for plant ✓ Gas drilling and pipelines ✓ Wood gas—logging and transport	None (inside buildings)	Minimal, local
Offshore wind farms	8 g CO_2-eq/kWhe	✓ No direct waste from turbines ✓ Low chemical waste from full technology chain	Quite good, mainly local opposition	None	Turbine manufacture, towing, cable laying	Remote, depends on distance offshore	None from shore
Solar PV-Si plant, PV-Si/PV-CdTe building	PV-Si plant: 34 g CO_2-eq/kWhe, PV-Si building: 33 g CO_2-eq/kWhe, PV-CdTe building: 18 g CO_2-eq/kWhe	✓ No direct wastes for panels. ✓ Low chemical wastes for full technology chain	✓ Generally very good for roof-mounted installations ✓ Possible local opposition to dedicated site installations	None	Manufacture and fabrication, transport and installation	Significant (self standing) to low (rooftop)	None
Solar thermal power plants	16 g CO_2-eq/kWh	Medium level of chemical waste from full technology chain	Generally good, but limited historic experience	None	Plant construction	Significant, but in generally remote location	Minimal local noise

Table 3
Barriers and drivers of RES technologies.

RES Technologies	Barriers	Drivers
Biomass CHP poplar/straw	✓ Lack of internalization of external costs in power generation ✓ Lack of effective policies to improve energy security and reduce CO_2 emissions ✓ Low conversion efficiency ✓ Transportation cost ✓ Feedstock availability (competition with industry and biofuels for feedstock, and with food and fiber production for arable land) ✓ Lack of supply logistics ✓ Risks associated with intensive farming (fertilizers, chemicals, biodiversity)	✓ Prospective energy price development ✓ Security of selling electricity (feed-in laws) ✓ Diversification of energy sources, energy import dependency ✓ Diversification of farmers' income ✓ Land use competition (en. crops): transport biofuels, biobased materials, food, nature conservation ✓ European policy framework supporting CHP
Fuel cells MCFC	✓ High cost of fuel cell stack and reformer ✓ Lifetime, degradation due to material science issues ✓ Reliability not yet proven ✓ Many competitors	✓ High electric efficiency ✓ Energy security ✓ Low criteria pollutant emissions ✓ Reduced vibration, high power to heat ratio
Offshore wind farms	✓ Lack of incentive schemes ✓ Impacts of variability on power system reliability ✓ Access to transmission ✓ Perceived visual and ecological impacts ✓ Structure of conventional electricity markets	✓ Increased performance and reliability ✓ Technology advances ✓ Larger turbines (when installed offshore) ✓ Increased manufacturing capacity
Solar, PV-Si plant, PV-Si/PV-CdTe building	✓ High production costs ✓ Low energy density (low efficiency and low number of operating hours per year) ✓ Intermittent source in an electricity grid	✓ Favorable regulatory framework ✓ Instrument for climate change policy ✓ Decentralized distribution system ✓ Technological and cross-sectorial spillovers ✓ Competitive and dynamic market ✓ Active role of venture capital
Solar thermal power plants	✓ High capital costs ✓ Limited potentials to connect South Europe and North Africa with Central Europe by use of high voltage direct current lines	✓ Objective of security of supply ✓ Enforced direct market support for RES (feed-in-laws) ✓ Preferring non-intermittent electricity suppliers ✓ Advanced side applications and side products ✓ Increasing demand for local added value ✓ Aiming at conflict neutral technologies

policies to promote it, the lack of internalization of external (transportation) costs, the feedstock availability and the risks of intensive farming. On the other hand, the feed-in laws provide secure selling perspectives, it could raise the farmers' income and it can certainly contribute to energy diversity and independence. These drivers and barriers are shown in Table 3 [24].

3.2. Molten garbonate fuel cells fed with wood gas

Molten Carbonate Fuel Cells (MCFC) belong to the high-temperature fuel cells and are used for electricity, heat in residential and commercial applications. Feeding them with wood gas constitutes a renewable source for electricity production. The typical MCFC systems have electrical capacities of 40–500 kWe, here a 250 kWe plant is considered, as shown in Table 1. Electrical efficiencies of mature systems without hybridization (e.g. coupled with a gas or steam turbine) reach 50% at start-up. However, today, these system efficiencies are only achieved at start-up with significant degradation over time, but total efficiency can reach up to 80–85% depending on the thermal integration of the system (e.g. return temperature, use of steam or hot water); an average of 50% efficiency is considered for this technology [25]. However, the electricity cost is the highest of the technologies considered in this study. Current capital costs are strongly dominated by the high Research and Development (R&D) cost [26]. The use of MCFC with wood gas gives a CO_2 life-cycle emission rate of 50 g CO_2-eq/kWh, as seen in Table 2 [25]. The use of MCMF produces moderate chemical waste, which is relatively less when feeding then with wood gas. The technology chain involves plant construction and operation, gas drilling and pipelines, as well as wood gas logging and transport. The use of wood gas also requires acceptance of wood harvest and transport. As Table 3 depicts, high costs and performance degradation are certainly blocking the deployment of this technology, although the favorable policies and the high efficiency makes MCMF a promising technology [25].

Fuel cell systems based on MCFC technology are under development in Italy, Japan, Korea, USA and Germany. Since the 1990s, MCFC systems have been tested in field trials in the range between 40 kWel and 1.8 MWel [27]. Among the fuel cell technologies being commissioned in 2006, MCFC dominate with more than 50% of the recent installations and numbering about 180 MCFC units worldwide [25]. Recently (May 2008) the European Parliament set up the Fuel Cells and Hydrogen (FCH) Joint Technology Initiative (JTI) that was proposed by the European Commission (EC) in autumn 2007 [28] with the aim to promote the R&D programme for fuel cells and hydrogen technologies in the European market [29].

3.3. Offshore wind farms

Offshore wind farms enjoy the advantage of having significantly higher wind speeds and more stable winds than onshore sites [30,31]. This leads to higher energy production at sea (up to 50% more electricity than their onshore cousins) and a longer turbine life. In addition, modern offshore wind turbines can also be remotely monitored and controlled, which provides advantages when regulating the power output [32]. The location of wind farms into the sea can reduce visual impact if the windmills are sited more than 12 miles (19 km) offshore and potentially allow siting near heavily developed coastal cities. In most cases,

though, the farms are situated away from large cities due to strong local opposition. An installation capacity of 24 MW is considered for a typical farm, with an expected load factor of 4000 h/years [32]. Construction time for this farm is about 2 years and the average cost of electricity 7.27 €cents/kWhe (see Table 1) [32]. Costs are largely dependent on water depth and distance from shore. Foundations, installation and grid connection are significantly more costly offshore. Turbine cost is typically 20% higher and towers and foundations perhaps 150% more [33]. For wind turbines most of the GHG emissions arise at the turbine production and plant construction. Life-cycle GHG emissions from wind turbines equal about 8 g CO_2-eq/kWhe [32]. The life-cycle assessment for this calculation includes the turbines, the internal cables, transformer station, marine transmission cable and a cable transmission station. Each of these includes materials, manufacturing, transport, erection, operation and disposal. The public acceptance is generally favorable, with local opposition present from area to area. Low chemical waste is produced from the full technology chain, as shown in Table 2. The increased performance, capacity and reliability of offshore wind farms has made them an attractive option for increased use, while the lack of incentives, the difficulty in getting access to transmission, the ecological impacts from the deep sea installations and the current structure of electricity markets are hindering their further deployment (see Table 3) [32].

Offshore installed capacity topped 1.1 GW in 2007, located in just six countries, including Denmark (420 MW), United Kingdom (300 MW), Netherlands (130 MW), Ireland (25 MW), and Sweden (135 MW) [33]. Significant offshore resources to be exploited in the near future have been identified in Finland, Ireland, Italy, the Netherlands, Norway, and Spain [34]. Prospects for 2015 look bright, with a total of more than 37 GW planned [35].

3.4. Solar photovoltaics (PV)

Wafer-based crystalline silicon currently represents the main technological route for the production of Photovoltaics (PV) modules. The main typologies of crystalline silicon are two [36,37]. Single-Crystalline Silicon (sc-Si) is characterized by atomic layers all oriented in the same direction in a single silicon crystal. Multi-crystalline silicon (mc-Si) is made of a set of single-crystalline, small-area, sc-Si clusters. On the other hand, thin films, such as Cadmium Telluride (CdTe), are obtained by depositing extremely thin layers of photosensitive materials on a low cost backing such as glass, stainless steel or plastic [38]. PV-Si panels can be used in solar plants or buildings, while PV-CdTe are mostly used on buildings. The main characteristics are shown in Table 1. Typical electricity capacities include 46.63 MW for plants, 0.42 MW for PV-Si buildings and 0.84 for PV-CdTe [37]. The load factor depends on exposure to sunlight, which is the reason why it is decreased in comparison to the other RES. The construction time is calculated at 2 years for the plant, and half a year for each building installation. The average electricity cost varies from 6.30 to 7.15 €cents/kWhe, the highest cost corresponds to PV-CdTe, while the capital cost is the lowest among the examined RES [37]. During the full operational life-cycle of PVs, the reported value of emitted CO_2-eq is estimated to be about 34 g CO_2-eq/kWhe for PV-Si plants, 33 g CO_2-eq/kWhe for PV-Si buildings and 18 g CO_2-eq/kWhe for PV-CdTe buildings [37,39]. The chemical waste from the technology chain is low and the public acceptance is favorable in general. The visual impact can be trivial when installed on rooftop buildings to significant for plants installed close to inhabited areas. Although PV installations have low energy density with high intermittency and comparatively high production costs, in most countries a favorable legal framework exists, such as feed-in tariffs along with instruments for climate change, such as the CDM, which promote such decentralized RES, as shown in Table 3 [37].

The aggregated research investments in PV technologies are estimated to have been 384 € million in 2007 [40]. Most of the public funds originated from countries with a comparably high deployment of PV, such as Germany, France, Italy and the Netherlands.

3.5. Solar thermal power plants

Solar thermal power generation systems capture energy from solar radiation, transform it into heat and generate electricity from the heat using steam turbines, gas turbines, stirling engines or pressure staged turbines [41]. Parabolic trough power plants consist of trough solar collector arrays and a conventional power block with steam turbine and generator. A heat transfer fluid, currently synthetic thermo oil is pumped through the collector array and heated up to 400 °C [42]. This oil is used to produce steam in heat exchangers before being circulated back to the array. The steam is used in a conventional steam turbine-based power plant. Parabolic trough power plants have the ability to generate larger amounts of electricity compared to other solar technologies. A typical electrical generation capacity is 400 MW for such a plant. The construction time (about 3 years), though, is bigger than any of the other RES compared, along with the capital cost, which reaches 3044 €/kWe [43]. The total solar-to-electricity efficiencies are calculated by combining the conversion of solar energy to heat within the collector (solar-to-heat efficiency) with the conversion of heat to electricity in the power block (heat-to-electricity efficiency), and thus are in the range of 18.5% [43]. The average electricity cost at 6.31 €cents/kWhe, in contrast to the high capital cost, is lower than all the other RES examined (See Table 1) [43]. Typical solar thermal power plant life-cycle GHG emissions amount to 16 g CO_2-eq/kWh [43,44] and load factor is similar to offshore wind farms. The chemical waste produced is of medium level and the public acceptance is generally good, although the historic experience is limited. The visual impact can be significant, but minimal if the plant is installed in remote areas. The parabolic trough power plants face a difficulty being introduced to Europe, due to high capital costs needed and the limited potentials to connect South Europe and North Africa with Central Europe by use of high voltage direct current lines [43]. However, it can enhance the security of supply and, when coupled with thermal storage to produce electricity in the absence of solar irradiation, can become an almost non-intermittent electricity supplier. It also benefits from policies, such as the feed-in tariff, as seen in Table 3 [43].

The first commercial parabolic trough power plants with a total capacity of 354 MW have already been in operation for over 20 years in California's Mojave Desert (USA). The Andasol 1 and Andasol 2 in southern Spain are the first parabolic trough power plants in Europe, with each site having a capacity of 50 MW. In 2011 628.5 MW of parabolic trough power plants were installed globally, indicating a rapid growth in the technology deployment [45].

4. Viewing nuclear energy technologies

Unlike most other low-carbon energy sources, nuclear energy technology has been in use for more than 50 years [11]. Nowadays, 29 countries worldwide are operating 440 nuclear reactors for electricity generation and 65 new nuclear plants are under construction in 15 countries. Moreover, nuclear power plants provided 14% of the world's electricity production in 2009 [46]. The EU member states France, Germany and Spain were in the top

10 Nuclear Generating Countries with 407.9 billion kWh, 133.0 billion kWh and 59.5 billion kWh respectively in 2010 [47].

4.1. European Pressurized reactor (EPR)

The European Pressurized Reactor (EPR) developed by Framatome–Siemens is a good representative of Generation III+ Pressurized Water Reactors. This nuclear technology uses moderately enriched (up to 5%) uranium oxide fuel or Mixed Oxide Fuel (MOX) and its net electrical output is in the range of 1600 MWe [48]. The EPR generates more electricity from a given quantity of fuel, thus conserving uranium resources (15% decrease in the amount of uranium used) and generating less waste (15% decrease). The Reactor Pressure Vessel (RPV) of the EPR is designed for a lifetime of 60 years [48]. The EPR has an increased efficiency of about 37% and an estimated annual generation of 12.6 TWh [49]. At about 3.01 €cents/kWhe, the average electricity cost is lower than half of the lowest of the respective RES technologies [49]. In addition, the capital cost is comparative to MCFC and lower than biomass gasification and solar thermal power plants, when comparing Tables 4 and 1. It should be mentioned that two EPR plants under construction in Finland and France have both faced serious delays and budget overruns of over 100% of the initial projections, according to announcements from officials. The two other EPR plants under construction in China, on the contrary, have faced no such issues. Up to four orders are expected in the United Kingdom, while others are under consideration in the United States.

As seen in Table 5, this reactor is speculated to exhibit close to zero CO_2 emissions, about 5 g CO_2-eq/kWhe for a full life-cycle, including fuel cycle, construction, operation, maintenance and decommission of the plant [49]. This number is significantly lower than the average number from the existing Generation II plants, which is about 65-66 g CO_2-eq/kWhe, according to surveys made by Sovacool [50] and Lenzen [51]. The plant life-cycle incorporates low chemical waste, but low to high level radioactive waste, depending on reprocessing of spent fuel. In addition, risks involve the possibility of misuse of fissile materials for making weapons and the risk of a severe accident, although very low due to enhanced safety features. The latter, in conjunction with high capital needs, constitute barriers towards the deployment of this nuclear technology. A barrier of great strength is also the public opinion (see Table 6) [49]. Social acceptability has not been the strong point of nuclear power and even the new and safer nuclear technologies cannot avoid this. The drivers that help this technology deploy are its greater safety features, its contribution to energy security, the low electricity generation costs, secure resources and the fact that it can provide large amounts of electricity in a framework of global rise in electricity demands, volatile and high prices of traditional fossil fuels [49].

4.2. European fast reactor (EFR)

The fourth generation of nuclear reactors (Generation IV) is being developed in an international framework to improve safety and economic performance, to minimize nuclear waste and to enhance proliferation resistance. It is expected to enter the market after 2030 [52]. Generation IV includes the European Fast Reactor (EFR), also called Sodium-cooled Fast Reactor (SFR), which runs on MOX fuel [53]. The estimated lifetime of the EFR extends to 40 years, with a projected construction time of 5.5 years [49]. The EFR has an even more increased efficiency of about 40%, with an estimated annual generation of 11.4 TWh. Its capacity is about 1450 MWe, while average electricity cost is depicted to be 2.68 €cents/kWhe, even lower than the EPR (see Table 4), although the capital cost is higher for this technology [49]. This reactor may have even fewer emissions of about 1 g CO_2-eq/kWhe for a full life-cycle [49], which is the lowest seen from Tables 2 and 5. The EFR constitutes a breeder reactor, which means it uses fast neutrons to generate more fissile material than it consumes because its neutron economy is high enough to breed fissile fuel from fertile material. In this way the nuclear fuel cycle can be almost closed and much less waste with even less radioactivity (decay within centuries) may be generated [49]. However, as with all nuclear technologies, social acceptance, public opinion, accident and safety risks also accompany the EFR. The concerns for proliferation or misuse are even greater in this case, since the enrichment technologies can be used for weapons proliferation and the diversion of bred fuel may be used in chemical processing to obtain plutonium or even to create a dirty bomb [49]. The drivers and barriers for this technology are similar to the ones described for the EPR.

5. Analysis and discussion

From an economic standpoint, a comparison between Tables 1 and 4 shows that solar thermal power plants have the highest capital cost, followed by Biogas CHP and then by the EFR. The EPR is on par with MCFC, while all the other RES have lower costs. This makes new nuclear technologies more appealing and financially attractive. This is enhanced when considering the average electricity generation cost, which is more than 50% lower with these nuclear technologies in contrast to the selected RES. On the other hand, the construction time needed is far more for the nuclear technologies than for the RES, which require 2–3

Table 4
Nuclear energy technologies characteristics and cost.

Characteristics	Units	Nuclear technologies	
		EPR	EFR
Fuel type		U235, 4.9%/mixed oxide	Mixed oxide
Electric efficiency	%	0.37	0.4
Electric generation capacity	MW	1590	1450
Load factor (expected)	hours/year	7916	7889
Annual generation (expected)	kWh/year	1.26E+10	1.14E+10
Construction time	years	4.8*	5.5
Plant life	years	60	40
Capital cost (net present value)	€/kWe	1498	1900
Total capital cost (net present value)	M€	2383*	2756
Average electricity cost	€cents/kWhe	3.01	2.68

* Delays of up to 6 years and cost overruns of more than 100% of the initial budget have been observed in the construction of two new plants in Finland and France, mainly due to quality control problems and manufacturing deficiencies. The construction of two new plants in Asia, though, is on or ahead of schedule.

Table 5
Sustainability factors of nuclear energy technologies.

Nuclear technology	Sustainability factors						
	GHG emission estimate (life-cycle)	Type of waste	Record of past public acceptance	Possible proliferation or misuse	Labor mix for technology chain	Visual disturbance	Noise
EPR	5 g CO_2-eq/kWhe	✓ Low to high level radioactive waste (spent fuel depends on fuel cycle and reprocessing) ✓ Low chemical waste from full technology chain	✓ No EPRs yet in service, so acceptance is limited to a few construction permits ✓ Past nuclear acceptance in general has been mixed to poor, especially after major accidents ✓ Accident risks, waste storage and proliferation may remain controversial	Possible misuse of fissile materials for making weapons	Fuel cycle, plant operation, construction, maintenance, refueling and demolition, waste reprocessing, waste disposal/ storage	Low to moderate, mainly dependent on whether or not cooling tower is present	Low
EFR	1 g CO_2-eq/kWhe	✓ Low to medium level radioactive waste (almost closed fuel cycle - reprocessing) ✓ Low chemical waste from full technology chain	✓ Limited prior acceptance in some countries ✓ Past nuclear acceptance in general has been mixed to poor, especially after major accidents ✓ Accident risks, waste storage and proliferation may remain controversial	✓ Misuse of enrichment technologies for weapons proliferation ✓ Diversion of bred fuel for chemical processing to obtain plutonium ✓ Possible misuse of diverted spent fuel for dirty bomb			

Table 6
Barriers and drivers of nuclear energy technologies.

Nuclear energy technologies	Barriers	Drivers
	✓ Safety (risk of severe accident, although very low) ✓ Waste management ✓ Potential risk of proliferation ✓ Financial risks (high capital needs) ✓ Controversial social acceptability	✓ Growing electricity demand on a world scale (especially in developing countries) ✓ High prices of fossil fuels and especially of gas for electricity generation ✓ Endorsement of policies for CO_2 mitigation, making fossil electricity generation very expensive ✓ Competitiveness: low electricity generation costs ✓ Low sensitivity to fuel costs ✓ Reliable energy resource: uranium supply in the short-medium term, and possibility of breeders

years at max. In addition, as mentioned in Section 4.1, there is always the probability of serious cost overruns and construction time delays, a fact that has happened to two new EPRs being built in Europe. Concerning electric generation capacity, the potential of the two nuclear technologies is far greater, considering also that nuclear energy has a large baseline energy output—the largest of any other energy source—and a large load factor of up to 90%, only surpassed by biomass gasification CHP (estimated load factor 91.3% from Table 1) in the present study. The other RES vary in their load factor, which depends on the feeding of wood gas for MCFC, on wind for offshore energy and on the solar irradiation for the solar technologies. Solar thermal power plants have a larger load factor than solar PV-Si due to the fact that they can be connected to thermal energy storage systems and produce electricity during the night or when solar irradiation is absent. Offshore wind farms are usually situated in areas with high wind potential and thus can produce electricity accounting for almost half a year of continuous operation.

Regarding full life-cycle GHG emissions, the nuclear technologies produce the fewest amounts with 5 g CO_2-eq/kWhe and 5 g CO_2-eq/kWhe emitted for the EPR and EFR respectively. Next in order are offshore wind farms, PV-CdTe and PV-Si installations, solar thermal plants and. Last with a substantial amount of 150 g CO_2-eq/kWhe (poplar) and 260 g CO_2-eq/kWhe (straw), biomass CHP seem to be the "worst pollutant" in comparison to all other RES exhibiting no more than 50 g CO_2-eq/kWhe. This is attributed mainly to the operating process of biomass CHP, which releases significant amounts of CO_2 [24]. When compared to traditional fossil fuels, whose emissions lay in the area of 450–1200 g CO_2-eq/kWhe [51], all examined technologies can contribute substantially to GHG mitigation. The leaders in this case are the EFR and EPR technologies. As an example, the operation of a 1 GW EPR

nuclear power plant in relation to a coal-fired plant with respective capacity can avoid the emission of about 6–7 million tonnes of CO_2 per year, as well as related airborne pollutants [54].

Chemical waste produced from the full technology chain of the RES technologies is in most cases low, with the exception of MCFC and Solar Thermal Power Plants, which have medium levels of waste deriving from their manufacturing and operating processes, as seen in Table 2. The nuclear technologies have low chemical waste as well, but produce radioactive waste that requires storage for a very long time. The amount of such waste depends on the nuclear fuel cycle. When the cycle is open, which means that no reprocessing of spent fuel is done after use in the reactor, more waste requiring disposal/storage is produced. On the contrary, a closed cycle means that reprocessing is applied and the amount left for disposal/storage is significantly reduced [55]. Moreover, in the EFR, which is a breeder reactor, more fissile material is generated than is consumed, a fact that offers great fuel economy and reduces the fuel needs for the plant operation. In addition, it can be used for reprocessing spent fuel and reduce the amount of waste requiring disposal.

Public acceptance of the specific RES examined is generally favorable, as depicted in Table 2. It is associated with the fact that renewables are considered carbon-free and non-pollutant energy sources, that are distributable and convenient for local use. In some cases, though, as is with wind farms and solar plants, local opposition can be strong and may be able to stop a renewable project from being implemented. In most cases this is associated with the visual impact of the RES technology (e.g. large wind turbines altering the natural view) and with the fact that many RES use up a great deal of land (e.g. hundreds of solar panels installed in a large area). A key element that differentiates the RES technologies from nuclear energy is the fact that they are considered accident-free. On the other hand, several nuclear power plant accidents and incidents involving the release of radioactive material to the environment have happened since the commercial deployment of nuclear technologies. They accidents have gained widespread attention and caused great influence on the public opinion. Most important ones, according to the International Nuclear Event Scale (INES) used by the International Atomic Energy Agency (IAEA), are the Chernobyl accident (1986) and the Fukushima Daiichi accident (2011), rated at level 7—the highest level—of the scale. Similar accidents involve the Kyshtym disaster in 1957 (level 6), the Three Mile Island accident in 1979 and the Windscale fire in 1957 (both level 5), among others. In addition, the very recent major Fukushima Daiichi accident has brought security issues to light and a consideration of the stress testing of all European nuclear plants. Moreover, some countries have altered their energy policies, such as Italy which was considering the use of nuclear power, and others, such as Germany have decided the gradual decommissioning of all nuclear plants [11]. It should be mentioned, though, that newly built and under construction reactors (Generation III, III+) have a perfect safety record to date since their first operation in 1996 [56].

The RES examined have no possibility of proliferation or misuse. On the other hand, the two nuclear technologies pose such threats, due to the nature of the fuel used and the need for reprocessing it. All reprocessing presents a proliferation concern, since it extracts weapons usable material from spent fuel. The most common reprocessing technique, PUREX, presents a particular concern, since it is designed to separate pure plutonium [55]. Spent fuel could also be used in the creation of a dirty bomb. In addition, fissile material may also be extracted and be used for weapons manufacturing. In the framework of the above, a Non-Proliferation Treaty has been established ever since 1968 and the vast majority of the world's countries have signed it.

When comparing drivers for the deployment of both RES and nuclear technologies from Tables 2 and 5, the following observations can be made. Many of the promising RES are boosted by a favorable policy framework. Either in the form of a market support scheme (e.g. feed-in tariff) or as an instrument for climate change policies (e.g. CDM), most of the RES can receive direct or indirect financial support for their further deployment. Their decentralized distributed nature is also of importance, since it allows them to be situated in remote and "difficult" areas, such as islands and isolated sparsely inhabited locations, where the central base-load distribution system cannot easily reach. This enhances energy security and security of supply in remote areas. In addition, continuous technological advances through R&D and increased mass production of technology components (e.g. solar panels) have raised the efficiency, performance, load factor and reliability of the technologies and at the same time made them more cost affordable over time.

In contrast to the above, the nuclear technologies examined are driven by the growing electricity demand in conjunction with the endorsement of policies for CO_2 mitigation, which makes the investment in fossil fuel plants unattractive. Low electricity costs, which means cheap energy, is also a positive driver for nuclear energy and is directly in conflict with the high electricity generation costs of the examined RES, which constitute one of the main barriers of the latter. Actually, not only electricity generation but also manufacturing costs is a barrier for the further development of the RES examined. Some of these technologies, namely Biomass CHP and MCFC, have additional costs related to forestry, harvest, transportation and gas drilling and pipeline installation. Biomass CHP also pose risks associated with intensive farming (fertilizers, chemicals, and biodiversity), while offshore wind farms and solar thermal plants face grid connection issues due to their remote installation location. Solar PV, though, is close to and has straight connection to the grid but is virtually an intermittent source in it. When it comes to the nuclear technologies examined, the barriers are specific and concern safety, waste management, financial risks (capital cost), proliferation and social acceptability. Apart from the financial cost, these parameters are different from the ones concerning the deployment of RES. The two first parameters have been enhanced in the presented technologies. New safety features have drastically reduced the possibility of a severe accident and a much less amount of waste is produced which needs to be handled by waste management processes. The capital cost for the two nuclear technologies per kWe is cheaper than previous generation plants, due to simpler design, although remains high when considering the entire investment [10]. The hazard of misuse of fissile material for weapons proliferation cannot be neglected and is still present in the new technologies and even more in the EFR, due to its breeding capabilities. It should be pointed out, though, that the proliferation problem is fundamentally a political problem and thus requires political solutions [10].

The comparison of the examined nuclear and renewable technologies shows why nuclear energy and RES are considered "opposites". On the one hand RES are regarded as clean, "accident-free", unlimited and easily distributable power sources. On the other hand, nuclear energy produces large amounts of cheap electricity but is considered "dirty" due to the radioactive waste it produces and dangerous due to the possibility of an accident and the subsequent health hazards and due to the proliferation problem it poses. Despite their differences, their future contribution towards sustainable development is likely to be substantial due to the increasing fossil fuel prices and the need to reduce GHG emissions [12]. Today one can also observe the fact that many developing countries (e.g. China and India) invest in nuclear power, due to their rapidly increasing electricity needs. On the contrary, developed countries (e.g. Denmark and Spain), which

are more energy sufficient are investing in RES, changing the energy mix towards more environmentally friendly technologies.

Supporters of nuclear technology have made efforts to aid its deployment. In 2008, the Ad Hoc Working Group on Further Commitments under the Kyoto Protocol (AWG-KP) to the United Nations Framework Convention on Climate Change (UNFCCC) sought ideas on how to enhance and improve the CDM and other emissions reduction mechanisms. Among the ideas proposed by UNFCCC Parties was allowing nuclear power projects under the CDM, although nuclear power plants have been disallowed as CDM projects up to 2012 [1]. A technical analysis of the proposal generated at the AWG-KP meeting was produced by the UNFCCC secretariat identifying two potential challenges. The first is a potentially increase in Certified Emission Reductions (CER) supply if many new nuclear plants are built that may decrease the value of carbon credits on the market and consequently reduce the incentive to transfer other emissions-reductions technologies via the CDM. This may result in industrialized countries accumulating enough CER credits that they increase their own GHG emissions, not to leave out the radioactive waste and other environmental impacts of this choice. The second challenge refers to the concept of "additionality", which is considered key to the CDM [57]. The main possibility for nuclear energy to make a significant contribution to GHG emissions reduction within the CDM would be after the Kyoto Protocol compliance period.

6. Conclusions

This paper has provided an overview of five promising renewable energy technologies and two new nuclear energy technologies, as regards to characteristics, specific sustainability factors, drivers and barriers for their further deployment. The potential and perspectives of CHP biomass, offshore wind farms, MCFC, solar PV and solar thermal, in contrast to the EPR and EFR have been presented in the framework of climate change mitigation. All of these technologies present substantial potential in decreasing the intensity of GHG emissions. The RES examined have very low GHG emissions (equal to or under 50 g CO_2-eq/kWhe), with the exception of CHP biomass, but which is still low compared to fossil fuel emissions. The nuclear technologies, on the other hand, have minimum impact on the environment in terms of GHG emissions. With as low as 5 g CO_2-eq/kWhe (EPR) or the estimated 1 g CO_2-eq/kWhe for the EFR, these are virtually carbon-free energy sources.

The RES produce no significant waste during their full lifecycle, only medium-level chemical waste in the worst case for solar thermal and MCFC. On the contrary, the EPR and EFR produce insignificant amounts of chemical waste, but significant radioactive waste. The amount of radioactive waste depends on the nuclear fuel cycle and the reprocessing of spent fuel. The EFR is able to breed new fuel via its design and thus can decrease the amount of waste at the end of its fuel cycle. Proliferation is also a major concern for the new reactors, but constitutes a political issue and subsequently its confrontation is a matter of political will. Visual impact from use of the technologies is greater for RES than nuclear and seems to be local in most cases.

Some of the RES presented, namely offshore wind and thermal solar already show significant deployment [3]. Others are hindered by barriers related to capital and production costs, reliability, intermittency and incentives, which may be addressed as the technologies become more mature and further experience is gained. Nuclear power, although deploying on a slow but steady rate with several plants scheduled to be built in the coming years, has yet to overcome its safety and environmental issues to gain the complete trust of people, especially after the recent Fukushima accident, which seems to have halted its expansion.

Acknowledgments

The current paper was partly based on research conducted within the framework of the project "New Energy Externality for Development and Sustainability (NEEDS)", financed by the European Commission—FP6—DG Research. The authors would like to specially thank Mr. Dimitrios Tsoumanis for his fruitful suggestions and comments to this paper. The content of the paper is the sole responsibility of its authors and does not necessarily reflect the views of the EC. In addition, Mrs. Charikleia Karakosta wishes to acknowledge with gratitude the Alexander S. Onassis Public Benefit Foundation for supporting her PhD research.

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